Spin Structure of Nucleon and Equivalence Principle

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Abstract

The partition of nucleon spin between total angular momenta of quarks and gluons is described by the energy momentum tensor form-factors manifested also in the nucleon scattering by weak classical gravitational field. Natural generalization of equivalence principle is resulting in the identically zero "Anomalous gravitomagnetic moment" being the straightforward analog of its electromagnetic counterpart. This, in turn, means the equal partition of momentum and total angular momentum, anticipated earlier.

1 Introduction.

Spin structure of the nucleon is known to be one of the most intriguing problems of non-perturbative QCD [1]. Its solution happened to deal with the fine details of the theory. In particular, the gluon spin momentum is intimately related to the axial anomaly, entirely responsible for the first moment of the relevant distribution [2] and manifested also as an x-dependent term [3].

The orbital angular momenta are the necessary counterparts of the spin one, required already by the leading QCD evolution [4, 5, 6]. The current mainstream of their studies is following the suggestion of X. Ji [5] to use the relation of *total* angular momenta to the particular matrix elements of Belinfante energy momentum tensors.

$$\langle p'|T^{\mu\nu}_{q,g}|p\rangle \;=\; \bar{u}(p')\Big[A_{q,g}(\Delta^2)\gamma^{(\mu}p^{\nu)} + B_{q,g}(\Delta^2)P^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha/2M]u(p) \quad (1)$$

where $P^\mu = (p^\mu + p^{\mu\prime})/2$, $\Delta^\mu = p^{\mu\prime} - p^\mu$, and $u(p)$ is the nucleon spinor. We dropped here the irrelevant terms of higher order in Δ, as well as containing $g^{\mu\nu}$, which will be discussed later. The parton momenta and total angular momenta are just

$$P_{q,g} = A_{q,g}(0),$$
$$J_{q,g} = \frac{1}{2}\left[A_{q,g}(0) + B_{q,g}(0)\right] \ . \tag{2}$$

Taking into account the conservation of momentum and angular momentum

$$A_q(0) + A_g(0) = 1 \tag{3}$$
$$A_q(0) + B_q(0) + A_g(0) + B_g(0) = 1 \tag{4}$$

one can see, that the difference between partition of momentum and orbital angular momentum is entirely coming from "anomalous" formfactors ($B_q(0) = -B_g(0)$).

The smallness of such a contributions comes from the models [7], QCD sum rules calculations [8] and chiral soliton models [9]. The careful analysis and rederivation [10] of the leading QCD evolution [6] was used to make a statement about the *identical* zero of the anomalous formfactor B. Moreover, just this general property was suggested in [10] as a reason for the smallness of the singlet anomalous magnetic moment, resulting from the approximate cancellation between proton (+1.79) and neutron (−1.91) values.

To prove this picture one should either study the higher orders and (especially) nonperturbative QCD contributions, or to look for a more general reason. In the present paper the latter approach is suggested. Namely, making use of the fact that the matrix element (1) is describing the interaction of nucleon with the classical external gravitational field one arrive to the interpretation of B as an "Anomalous Gravitomagnetic Moment" (AGM), being the straightforward analog of its electromagnetic counterpart. The natural extension of the famous Einstein equivalence principle is resulting in the zero AGM. As a byproduct, one can see, that the helicity of any Dirac particle (say, massive neutrino), is not flipped by the rotation of astronomical objects.

2 Nucleon in the external gravitational field.

Let us start with the more common case of the interaction with electromagnetic field, described by the matrix element of electromagnetic current,

$$M = \langle P'|J^\mu_q|P\rangle A_\mu. \tag{5}$$

This matrix element at zero momentum transfer is fixed by the fact, that the interaction is due to the *local* U(1) symmetry, whose *global* counterpart is producing the conserved charge (and of course is depending on the normalization of eigenvectors $\langle P|P'\rangle = (2\pi)^3 2E\delta(\vec{P} - \vec{P'})$).

$$\langle P|J_q^\mu|P\rangle = 2e_q P^\mu, \tag{6}$$

so that in the rest frame the interaction is completely defined by the scalar potential:

$$M_0 = \langle P|J_q^\mu|P\rangle A_\mu = 2e_q M\phi \tag{7}$$

At the same time, the interaction with the weak classical gravitational field is:

$$M = \frac{1}{2}\sum_{q,G}\langle P'|T_{q,G}^\mu|P\rangle h_{\mu\nu}, \tag{8}$$

where h is a deviation of metric tensor from its Minkowski value. The relative factor 1/2, which will play a crucial role, is coming from the fact, that the variation of the action with respect to the metric is producing an energy-momentum tensor with the coefficient 1/2, while the variation with respect to classical source A^μ, is producing the current without such a coefficient. It is this coefficient, that guarantee the correct value for the Newtonian limit, fixed by the *global* translational invariance

$$\sum_{q,G}\langle P|T_i^{\mu\nu}|P\rangle = 2P^\mu P^\nu, \tag{9}$$

which, together with the approximation for h (with factor of 2 having the geometrical origin) [11]

$$h_{00} = 2\phi(x) \tag{10}$$

is resulting in the rest frame expression:

$$M_0 = \sum_{q,G}\langle P|T_i^{\mu\nu}|P\rangle h_{\mu\nu} = 2M \cdot M\phi, \tag{11}$$

where we used the same notation for gravitational and scalar electromagnetic potentials, and identified normalization factor $2M$ in order to make the similarity between (7) and (11) obvious. One can see that the interaction with gravitational field is described by the charge , equal to the particle mass, which is just the equivalence principle. It is appearing here as low energy theorem, rather than postulate. The similarity with electromagnetic case allows to clarify the origin of such a theorem, suggesting, that the interaction with gravity is due to the *local* counterpart of *global* symmetry, although it may be proved starting just from the Lorentz invariance of the soft graviton approximation [12].

The situation with the terms linear in Δ is different for electromagnetism and gravity. While such a term is defined by the specific dynamics in the electromagnetic case, producing the anomalous magnetic moment, the similar contribution in the gravitational case is entirely fixed by the angular momentum conservation (4), which was known in the context of gravity for more than 20 years [13, 14]. [1]. It means, in terms of the gravitational interaction, that **Anomalous Gravitomagnetic Moment (AGM) of any particle is identically equal to zero**.

Let us clarify this statement, which is not restricted to the nucleon or spin-1/2 Dirac particle. The presence of Dirac spinors in the parametrization (1) is actually not crucial. To show that, it is convenient to use the equation of motion in order to attribute all the Δ-dependence to the *anomalous* formfactor $P^\mu \bar{u}\sigma^{\nu\alpha}u\Delta_\alpha$. As soon as the linear Δ-dependence is already extracted, the spinors can be taken at the same momentum, which is convenient to choose as an average one P, and calculation of the matrix element is reduced to the trace of density matrix:

$$\bar{u}(P)\sigma^{\nu\alpha}\Delta_\alpha u(p) = Tr\rho(P)i\sigma^{\nu\alpha}\Delta_\alpha =$$
$$Tr\frac{1}{2}(\hat{P}+M)(1+\hat{S}\gamma_5)i\sigma^{\nu\alpha}\Delta_\alpha = 2i\epsilon^{\rho\sigma\nu\alpha}P^\rho S^\sigma \Delta^\alpha \qquad (12)$$

The constraint (4), by considering the matrix element of the projection of Pauli-Lubanski operator, may be now easily generalized to the particle of *any* spin, so that, for the *total* conserved energy momentum tensor of all the

[1] The reason is that the structure of Poincare group is more reach than that of $U(1)$ group.

constituents is (c.f. [15]):

$$\langle P'|\sum T^{\mu\nu}|P\rangle \;=\; 2P^\mu P^\nu + iP^{(\mu}\epsilon^{\nu)\sigma\rho\alpha}P^\rho S^\sigma \Delta^\alpha/M. \tag{13}$$

Like in the spin $1/2$ case, S is the average spin in any of the states $|P>, |P'>$ (the difference between which is inessential, as soon as linear terms in Δ are considered, and we postpone the discussion of the spin-flip case.)

As soon as the formfactors in spin-1/2 case differ from the ones for the matrix element of vector current J^μ by the common factor P^ν, one may define *gyrogravitomagnetic ratio* in the same way as common gyromagnetic ratio, and it should have Dirac value $g = 2$ for particle of any spin J:

$$\mu_G = J \tag{14}$$

which coincide with the standard Dirac magnetic moment, up to the interchange $e \leftrightarrow M$, making the Bohr magneton equal to $1/2$.

However, the situation changes if one define the gyrogravitomagnetic moment as a response to the external gravitomagnetic field. The ϵ tensor in the coordinate space produce the curl, and the gravitomagnetic field, acting on the particle spin, is equal to

$$\vec{H}_J = \frac{1}{2} rot\vec{g};\;\; \vec{g}_i \equiv g_{0i}, \tag{15}$$

where factor $1/2$ is just the mentioned normalization factor in (10). The relevant off-diagonal components of the metric tensor may be generated by the rotation of massive gravity source [11].

There is also another effect, induced by this field: the straightforward analog of Lorentz force [11], produced by the first (spin-independent) term in (24). In that case the gravitomagnetic filed, for the low velocity of the particle (such a restriction is actually inessential, as we can always perform the Lorentz boost, making the particle velocity small enough) is:

$$\vec{H}_L = rot\vec{g} = 2\vec{H}_G, \tag{16}$$

Consider now the motion of the particle in the gravitomagnetic field. The effect of Lorentz force is reduced, due to the Larmor theorem, (which is also valid for small velocity) to the rotation with the Larmor frequency

$$\omega_L = \frac{H_L}{2}. \tag{17}$$

This is also the frequency of the *macroscopic* gyroscope dragging. At the same time, the *microscopic* particle dragging frequency is

$$\omega_J = \frac{\mu_G}{J} H_J = \frac{H_L}{2} = \omega_L. \tag{18}$$

The common frequency for microscopic and macroscopic gyroscope is just the Larmor frequency, so that the gravitomagnetic field is equivalent to the frame rotation. This should be considered as a Post-Newtonian manifestation of the equivalence principle.

Let us make here a brief comparison with the literature. The low energy theorem discussed here is the necessary ingredient for validity of gravitational Larmor theorem [16], which otherwise require an arbitrary assumption about the "classical" gyrogravitomagnetic ratio, say, for electron [17]. At the same time, the equality of the "classical" and "quantum" frequencies was found long ago [14] by comparison of the quantum spin-orbit interaction with the classical calculated earlier [18]. Our approach clarify the origin of this equality, as a cancellation of "geometrical" factor 1/2 in (10) and "quantum" value 2 of gyrogravitomagnetic ratio. Note that for free particle the latter coincides with the usual gyromagnetic ratio, and such a cancellation provides an interesting connection between geometry, equivalence principle and special renormalization properties (cancellation of strongest divergencies) for particles with $g = 2$. Another interesting connection is provided by the fact, that it is just the deviation from $g = 2$, which determine the Gerasimov-Drell-Hearn sum rule for particle with arbitrary spin [21].

The crucial factor 1/2 makes the evolution of the particle helicity in magnetic and gravitomagnetic fields rather different. The spin of the (Dirac) particle in the magnetic field is dragging with the cyclotron frequency, being twice larger than Larmor one. It coincides with the frequency of the velocity precession so that helicity is conserved. At the same time, the gravitomagnetic field is making the velocity dragging twice faster than spin, changing the helicity. This factor of 2, however, is precisely the one required by the possibility to reduce all the effect of gravitomagnetic field to the frame rotation. While spin vector is the same in the rotating frame and is dragging only due to the rotation of the coordinate axis, the velocity one is transformed and getting the additional contribution, providing factor 2 to Coriolis acceleration. The Dirac particle helicity conservation in magnetic field allows to find semiclassical interpretation of anomalous magnetic moment and axial

anomaly [19]. The geometrical factor 1/2 is providing the contact of these phenomena with the equivalence principle. The similarity between gravitational and electromagnetic interactions, leading to the simplifications of the field equations for $g = 2$ was mentioned in [20], although the low energy-theorem, guaranteeing the appearance of this value in the case of gravity, was not used.

Note that all the consideration is essentially based on the smallness of the particle velocity, achieved by the mentioned Lorentz boost, and therefore do not leading to the loss of generality.

Let us consider massive particle scattered by rotating astrophysical object. The effect of the gravitomagnetic field is reduced to the rotation of the local comoving frame, which is becoming inertial at large distances before and after scattering. Consequently, the helicity is not changed by gravitomagnetic field, which is confirmed by the explicit calculation of the Born helicity-flip matrix element in the case of massive neutrino [22]. The reason for that may be also deduced from the structure of the matrix element (24), where, in general, the symmetric combination of spins $(s+s')/2$ should appear, which is zero in the spin-flip case.

Note that massless particles are not coupled to gravitomagnetic field at all, as one cannot construct the pseudovector in (24), because vectors s and p are collinear (c.f. [14]). At the same time, for arbitrary light longitudinally polarized massive particle, one get the mass-independent term $P^{(\mu}\epsilon_{\perp}^{\nu)\alpha}\Delta_\alpha$, where $\epsilon_\perp$ is a two-dimensional antisymmetric tensor in the plane, orthogonal to particle momentum.

It may seem, that the equivalence principle should exclude the possibility of helicity flip in the scattering by gravity source at all. This is, however, not the case, if usual Newtonian-type "gravitoelectric" force is considered. Its action is also reduced to the local acceleration of the comoving frame, in which the helicity of the particle is not altered. However, the comoving frame after scattering differs from the initial one by the respective velocity $\delta\vec{v} = \int \vec{a}dt$. The corresponding boost to the original frame is, generally speaking, changing the helicity of the massive particle (the similar effect for the gravitomagnetic field is just the rotation for the solid angle $\delta\vec{\Omega} = \int \vec{\omega}dt$ and does not affect the helicity). The same boost may be considered as a source of the famous deflection of particle momentum $\delta\phi \approx |\delta\vec{v}|/|\vec{v}|$. The average helicity of the completely polarized beam after such a scattering may

be estimated in the semiclassical approximation as $< P > \approx cos\phi \approx 1 - \phi^2/2$. Due to the correspondence principle, this quantity may be expressed as

$$< P >= \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} \approx 1 - 2\frac{d\sigma_{+-}}{d\sigma_{++}}, \tag{19}$$

where $d\sigma_{+-} \ll d\sigma_{++}$ - the helicity-flip and non-flip cross-sections, respectively. Comparing "classical" and "quantum" expression for $< P >$, one get

$$\frac{d\sigma_{+-}}{d\sigma_{++}} \approx \frac{\phi^2}{4} \tag{20}$$

To check this simple approach, one may perform the calculation of this ratio for the Dirac particle scattered by the gravitational source. In the Born approximation, the result is easy to find:

$$\frac{d\sigma_{+-}}{d\sigma_{++}} \approx \frac{\phi^2}{4(2\gamma - \gamma^{-1})^2}. \tag{21}$$

This expression is coinciding with the estimate (20), as soon as the particle is slow ($\gamma = E/m \to 1$), while for the fast particles

$$\frac{d\sigma_{+-}}{d\sigma_{++}} \approx \frac{\phi^2}{16\gamma^2}. \tag{22}$$

Such an effect should, in particular, lead to the helicity flip of any massive neutrino. It is very small, when the scattering by the single object is considered, but may be enhances while neutrino is propagating in Universe. Should the propagation time be large enough, the effect would result in unpolarized beam of the initially polarized neutrino, effectively reducing its intensity by the factor of 2.

The manifestation of post-Newtonian equivalence principle is especially interesting, when "gravitoelectric" component is absent. Contrary to electromagnetic case, one cannot realize this situation through cancellation of contributions of positive and negative charges. At the same time, one may consider instead the interior of the rotating shell (Lense-Thirring effect). Especially interesting is the case of the shell constituting the model of Universe,

whose mass and radius are of the same order, when the dragging frequency may be equal to the shell rotation frequency, which is just the Mach's principle [23]. One should note, that the low energy theorem, guaranteeing the unique precession frequency for all quantum and classical rotators, is the necessary counterpart of the Mach's principle.

3 Universal nullification of anomalous gravitomagnetic moment as an extension of equivalence principle.

Up to this moment, we considered the gravitational interaction of the particle, being the eigenstate of the momentum and spin projection and described by the conserved energy-momentum tensor. Any assumptions on the particle locality except the locality of energy-momentum tensor were unnecessary.

We are now ready to postulate the following straightforward generalization of this principle:

Contributions of all fundamental constituents to the Anomalous Gravitomagnetic Moment of composite particle are zero

The main reason is the stability of the particle with respect to action of gravitomagnetic field. To illustrate the latter, one may consider the following gedankenexperiment. Suppose the (attractive) interaction between two particles is adiabatically increasing, so that they finally form the bound state. Originally the AGM of both particles are equal to zero. When interaction is increasing, the momenta and angular momenta of particles are no more conserved, and this may generate, in principle, their non-zero AGM (equal to each other, up to a sign). The gravitomagnetic field should force the particles spins to rotate with the different frequencies, affecting in that way the structure of the bound state. If the bound state is "local" in the sense that its intrinsic structure is never affected by gravity, such an opportunity is excluded, and AGM is zero for each of interacting particles separately.

The extension of this property to quarks and gluons, which do not exist as a free particles, is equivalent to the statement, that nucleon properties are not affected by the gravity. More formally, this should mean that for each term in the QCD action in the gravitational field, which may be transformed to its flat-space form by the local coordinate transformation, this local form would be sufficient to calculate the relevant matrix element of the energy-momentum tensors.

The main consequence of such a hypothesis is a relation of two rather

different fields of physics: gravity and strong interactions. The situation is somehow similar to the one existed in hadron electrodynamics before QCD. It was possible to establish some properties of electromagnetic interactions of hadrons (and, consequently, of matrix elements governed by strong interactions) starting from gauge symmetry and corresponding Ward identities.

The existence of such a connection does not require a deep relation like unified theory. At the same time, due to the generality of gravity the correspondent "gravidynamics of hadrons" may provide more elaborate links.

In any case, one may get some information about the gravitational interactions of nucleons performing the experimental and theoretical studies of strong interactions. Let us briefly outline the main possible connections and directions.

The immediate problem one meet decomposing the quark and gluon contributions to energy-momentum tensors is the appearance of the structures (at the zero order in Δ) in (1) proportional to $g^{\mu\nu}$. The natural way of handling is the extraction of the traceless part [25]:

$$\langle p|T^{\mu\nu}_{q,g}|p\rangle \;=\; \langle p|T^{\mu\nu}_{q,g}-\frac{1}{4}T^{\mu\mu}_{q,g}|p\rangle+\langle p|\frac{1}{4}T^{\mu\mu}_{q,g}|p\rangle \qquad (23)$$

The traceless and trace parts are providing 3/4 and 1/4 of expectation value of T^{00} component, related to the particle *inertial* mass [25]. At the same time, the interaction with the external gravitational field (10) is providing, due to its space components $h^j_i = -2\phi\delta^j_i$, the respective contributions 3/2 and $-1/2$ to its *gravitational* mass. This sign difference should not come as a surprise, because the Einstein equations differ just by the sign, when the traces and traceless parts of the tensors $T^{\mu\nu}$ and $R^{\mu\nu}$ are considered.

We are now in a position to postulate that it is just *traceless* part of the forward matrix element, which should be equal, due to equivalence principle, to the linear in Δ part of the non-forward one.

To justify this choice, one might recall that it is the traceless part allowing for the natural separation of the quark and gluon contribution to the nucleon [25] mass. Also, the linear in Δ term (24) is manifestly traceless. Another support is coming from the perturbative calculations. The matrix elements of energy momentum tensors of electrons and photons acquire the logarithmycally divergent contributions, cancelled in their sum. This problem, at leading order(LO), is similar to the calculation of QED corrections

to gravity coupling [27]. It is sufficient to consider the matrix elements of either electron or photon energy momentum tensor switched between free electron states, and the latter case is more simple, being described by the single diagram. It is enough to consider the terms of zero and first order in Δ. The divergent contribution to the former is appearing in the traceless part and may be identified with the second moment of spin-independent DGLAP kernel $\int_0^1 dx x P_{Gq}(x)$. The linear term is known from the orbital angular momentum calculations [5, 6] and is also equal to that quantity, so that AGM is really zero.

To summarize, the extension of the equivalence principle for the fundamental fields in the constituent particle is:

$$\langle P'|T_i^{\mu\nu}|P\rangle = N_i[2(P^\mu P^\nu - g^{\mu\nu}/4M^2) + \frac{i}{M} P^{(\mu}\epsilon^{\nu)\sigma\rho\alpha} P^\rho S^\sigma \Delta^\alpha] + O(g^{\mu\nu}, \Delta^2). \quad (24)$$

As soon as the coefficient of the traceless part is equal to that of $P^\mu P^\nu$, the trace term in square bracket may be omitted; in particular, for quarks and gluons in nucleon one get:

$$B_{q,g}(0) = 0; \quad (25)$$

$$P_{q,g} = J_{q,g} \quad (26)$$

4 Discussion and Conclusions

The main result of this paper is the relation between gravity and strong interactions, analogous to the relation between electrodynamics and strong interactions, provided by the methods of electrodynamics of hadrons. One should clearly distinguish the consideration of the stable composite particle and its constituents. While in the first case the zero AGM is a consequence of the conservation of momentum and angular momentum, the similar statement for its constituents should be considered as an extension of equivalence principle. Let us briefly discuss the main points for these related problems.

For composite particle as a whole, the presented derivation of zero AGM allows to understand the reason for the equal dragging frequencies for macroscopic and microscopic rotators. This is due to the intimate relation between the universal Dirac value of gyrogravitomagnetic ratio (related, in turn, to

the special renormalization properties of the higher spin particles with $g = 2$) and geometrical factor for the effective gyrogravitomagnetic field. One should not apply any notion of locality for the particle in question, except that it should be the eigenstate of the momentum and orbital angular momentum and, due to the uncertainty principle, is *not* local in the real space; one may recall the Dirac electron, which is point-like in the dynamical sense, but may be described by the plane wave. Also, the locality of energy momentum tensor is important. The universality of gyrogravitomagnetic ratio is resolving the ambiguity existing in the literature concerning the particles motion in the external gravitomagnetic fields, completing the proof of the gravitational Larmor theorem, and constitute the necessary ingredient of Mach's principle. In particular, the equivalence principle is not allowing for helicity flip of any massive particle (say, neutrino) due to the rotation of massive astrophysical object passed by this particle. At the same time, the Newtonian "gravito-electric" field is resulting in the helicity flip, which may be related, in the semiclassical approximation, to its deflection angle.

Passing to the structure of the composite particle, one should find the nullification of its total AGM as a new general constraint which should be imposed for *any* bound state, and in particular for heavy or light nuclei. The simplest case is provided by the deuteron, for which the isotopic structure is making the AGM to be related to the usual AMM: namely, neglecting the sea quarks contributions they are represented by the consecutive moments of skewed parton distribution [5, 26]. Taking into account the approximate cancellation of proton and neutron AMM (which may be explained [10] as resulting from the zero AGM of quarks in protons, to be discussed below), one should find small AMM (to be manifested in the experiments with polarized deuterons [24]) and zero AGM. At the same time, for non-isosinglet nuclei, there is no reason to expect the small AMM, while zero AGM is providing the non-trivial constraint for their structure. Moreover, the same reasoning may be applied for the atoms, as soon as they are representing the *pure* quantum states, and even to the coherent macroscopical structures in the condensed matter physics.

The zero AGM of constituents and, moreover, of the fundamental fields, is the new hypothesis, based on the locality of the particle. The specific role of traceless part of the energy-momentum tensor might be compared to the modifications of gravity theory [28] providing the natural solution of cosmological constant problem. The theoretical and experimental studies of

the hadronic matrix elements offer the possibility to understand the hadron behavior in gravitational fields. From the other side, the gravitational experiments [29] might be used to understand the hadron structure.

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